バーゼル地熱フィールドでの水圧刺激にともなう誘発有感地震の発生メカニズムに関する研究

著者	椋平 祐輔
号	10
学位授与機関	Tohoku University
学位授与番号	学術(環)博第170号
URL	http://hdl.handle.net/10097/59061

	むくひら　ゆうすけ
氏　　　　　名	椋　平　　祐　輔
授　与　学　位	博士（学術）
学 位 記 番 号	学術（環）博第１７０号
学位授与年月日	平成２５年３月２７日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院環境科学研究科（博士課程）環境科学専攻
学 位 論 文 題 目	バーゼル地熱フィールドでの水圧刺激にともなう誘発有感地震の発生メカニズムに関する研究
指　導　教　員	東北大学教授　土屋　範芳
論 文 審 査 委 員	主査　東北大学准教授　浅沼　宏　　東北大学教授　土屋範芳 東北大学教授　　伊藤高敏

論 文 内 容 要 旨

1. Introduction and background

Induced microseismicity that have been felt at the ground surface (hereafter referred to as “large events”) have been reported at various commercial-scale EGS/HDR sites (Majer et al., 2007), oil/gas reservoirs (Suckale, 2010), and CCS sites (Evans et al., 2012). Some of the large events having *Mw* (moment magnitude)>2.0 was not only be felt on the surface but also brought considerable damages to the building. Therefore, the occurrence of the large events has been recognized as one of the critical problems to be solved. However, some problems in quality of the dataset of the large events and seismic monitoring network prevent us to understand the physics behind the large events. This study tackled this problem using the data set from Basel Geothermal Field, where signals with wideband and high signal to noise ratio natures have been collected. The author concluded that the data set from Basel has sufficient quality for precise investigation of the physics behind the large events.

In this study, fundamental characteristics of the large events were firstly investigated using super-resolution processing techniques. Several physical models were also considered to interpret the observed characteristics of the large events, trigger mechanism of the shear slip on existing fractures, and the control factor of magnitude of seismic events. The appropriateness of the proposed models was evaluated comparing the observations from the analyses. Finally, the most reasonable physical model to describe the physics of the large event was concluded.

2. Characteristics of the large events at Basel

Chapter 2 describes analyses of seismic events including the large events and observation from the analyses, which included hypocenter location, time series of occurrence of seismic events, similarity in waveform among the large events and smaller events, fault plane solutions (FPSs), and source parameters as stress drop. It has been revealed that some of the large events were classified into deep and shallow large events by their characteristic such as occurrence time and hypocenter location. The characteristics of the deep/shallow large events are summarized in Table 1.

Table 1: Summary of the characteristics of the deep/shallow large events.

	Deep large events (4600 m~)	Shallow large events (~3800 m)
Magnitude	Large events did not follow Gutenberg-Richter scaling law	
Occurrence time	- Occurred during or just after the stop of the injection	- Occurred after one or two month of the stimulation
Hypocenter location	- Occurred within the seismic cloud or the edge of the seismic cloud - Occurred from the seismically active area at just after the stimulation	- Occurred outside of the seismic cloud - Located both side of the seismic cloud
Time series of occurrence	- No apparent extension of the seismic cloud after the occurrence of the large events	- No fore shock and after shock for the shallow large events were observed
Similarity in waveform	- High similarity in waveforms with the neighboring events	- Low similarity in waveform with most of the seismic events
Fault plane solutions	- WNW-ESE (3) and NNW-SSE (1) azimuth - Some large events occurred from fault plane of the largest events	- N-S azimuth (2)
	- Types of FPS for all large events were strike slip. - Large events occurred from mainly two types of sub vertical fault planes which have N-S azimuth or WNW-ESE azimuth.	
Stress drop	- Stress drop of the large event were 1~3 MPa - Relationship among the source parameters suggest that the constant stress drop scaling low in a series of seismic events	

3. Physical model for the mechanism of the large events at Basel

Several physical models were proposed to describe location and orientation of the existing fracture system where the large events occurred, shear slip of the large events, trigger mechanism of the shear slip of the large events, and control factor of the magnitude of the seismic events. Numerical analyses were conducted based on physical models to verify their consistence.

Previous study revealed that fracture system within the Basel geothermal reservoir consists of pair of conjugate fracture planes to the stress state (Asanuma et al., 2007). Identification of the fault plane of the large events showed that there were four types of significant fracture planes in the reservoir and that seismic activity distributed asymmetrically on these conjugate planes. The physical model for existing fracture system where the large events occurred was investigated from previous study and these observations.

Seismic moment is determined by the fault area and displacement of the shear slip of existing fracture from the theory of the seismology. Three patterns of the shear slips are expressed by a combination of fault area and displacement as physical models for shear slip of the large events. The relationship among the source parameters was investigated in order to reveal characteristics of the shear slip. It was suggested from the observations on the relationship between the seismic moment and the fault area that a series of the seismic events followed constant stress drop scaling low.

Trigger mechanisms of the shear slip on the existing fracture were investigated from Coulomb failure criterion, dominant equation for the shear slip of existing fracture. It is considered as physical model for trigger mechanism that increase in pore pressure or change in stress state on fracture plane was possible trigger of the shear slip. Pore pressure was estimated from Coulomb failure criterion using the information on the stress state and the FPSs. Meanwhile, spatiotemporal distribution of the pore pressure was estimated by diffusion model (Shapiro et al., 2007). As a result of the analysis, it is revealed that the large events occurred under relatively low critical pore pressure. Pore pressure estimated by the diffusion model increased as much as MPa only in the near field from a feed point. Diffusion model simulated pore pressure perturbation even after one or two month of the stimulation in the far field. Static stress change caused by the shear slip of the preceding events was calculated with Coulomb 3 software (Toda et al., 2005). Most of the stress changes on the fault plane of the large events were less than 1.0 MPa. Thermal stress was also estimated based on the pore pressure distribution by diffusion model. Temperature difference was observed only in the vicinity of the feed point, generating 10~80 MPa of thermal stress. It is found that the pore pressure estimated from the Coulomb failure criterion and thermal stress can cause considerable change to trigger shear slip. It is also found that changes in the many of the parameters were not enough large to trigger the shear slip and their spatial distribution were fairly localized. No parameters analyzed in this study showed significant increase before the occurrence of the large events.

This study proposed models that the critical pore pressure and the stress state on the fault plane determined the magnitude of the seismic events. The analysis to investigate the relationship showed there was no clear correlation between critical pore pressure and magnitude of the seismic events. Furthermore, large events occurred from the fault planes with relatively small critical pore pressure. Meanwhile, there was some relationship that the seismic events with large magnitude occurred from the fault plane with high shear stress.

4. Discussion on the mechanism of the large events at Basel

Physical models for the mechanism of the large evens were discussed considering the characteristics of the large events and the result of the analyses based on the physical models. Appropriate explanations were finally concluded for the four topics in table 2.

It is concluded that the deep large events occurred from the fracture system that consists by weakest pair of conjugate fracture plane to the orientation of the maximum horizontal stress (N144E±14°). Three of the deep large events occurred from one of the conjugate fault plane with WNW-ESE azimuth and fault plane of two of them were part of the fault plane where the largest events occurred. Similarities in waveforms among these three deep events were fairly high, suggesting that the three large events occurred on common fault plane. Meanwhile, the rest of the deep large event occurred from the other of conjugate plane with almost N-S azimuth. Shallow large events were likely to occur from the fault planes, which were spatially independent from main fracture system. Orientation of the fault planes of the shallow large events were nearly N-S and nearly parallel to the orientation of the seismic cloud. There is some possibility that the shallow large events occurred within the seismic cloud as the shallow large events had 100 m of spatial error at the hypocenter determination. However, low similarity in waveforms of the shallow large events to the other seismic events suggests that mechanism of the shallow large events is not identical to that of other seismic events occurred within seismic cloud. According to this, it is reasonably concluded that the shallow large events occurred from outside of the seismic cloud.

Evaluation of the relationship among source parameters suggested that a series of the seismic events including the large events followed constant stress drop scaling low. It is interpreted from this scaling low that the shear slips which originated the large events are identical physical phenomena to the shear slip of smaller events although there are some differences in the scale of the fault are or displacement. Therefore, it is concluded that the large events have origin in the peculiar physical phenomena like a shear slip with extremely high stress drop.

Considering observations based on the physical model for the trigger mechanism of the large events, it can be concluded that increase in pore pressure was the most reasonable trigger mechanism because diffusion pore pressure, static stress change, and thermal stress did not change as much as the pore pressure and their changes were fairly localized. However, many of the large events had not occurred since 5th day of the hydraulic stimulation, even though the large events occurred from the fault plane on which shear slip can be induced by small increase of the pore pressure. Furthermore, many smaller events had occurred before the occurrence of the large events, suggesting that pore pressure in the area had already increased. These observations indicate that only simple increase in pore pressure cannot explain the occurrence of the large events. In fact, no parameters analyzed in this study showed significant increase before the occurrence of the large events. It cannot be neglected that many of the large events occurred just after the shut in. There is some possibility that behavior of the pore pressure at the shut in trigger the shear slip of the large events. It can be also considered that thermal stress triggered the shear slip of the large events because thermal stress caused considerable change.

Analyses for the control factor of the magnitude revealed that pore pressure did not correlate with the magnitude of the seismic events. Furthermore, the large events occurred from the fault plane with low increase in pore pressure. The large events were likely to occur from the fault plane with high shear stress. In contrast, many smaller events also occurred from the fault plane with high shear stress. Thus, it is concluded that shear stress is one of the control factor for the magnitude of seismic events. The other control factor which brought large part of the failure should be investigated.

5. Conclusions

This study revealed the fundamental characteristics of the large events occurred from Basel geothermal filed and also investigated the fracture system where large evens occurred, shear slip of large events, trigger mechanism of shear slip of large events, and control factor of magnitude, proposing the physical model. Finally, most part of the mechanism of the large events was successfully explained with the physical model.

論文審査結果の要旨

近年，地熱，石油・天然ガス開発，二酸化炭素地下貯留等の分野において，流体の生産，および注入にともない，有感地震が誘発される事例が各国で報告され，本分野における重大な環境影響のひとつとして，その解決が望まれている。本研究はスイス，バーゼルでの地熱開発プロジェクトにおいて記録された，高品質，すなわち，広帯域，高SN比，大ダイナミックレンジ等の特徴を有する実データの解析をベースに，誘発有感地震の発生メカニズムを解明することを目的として実施したものであり，その成果を全５章の論文としてまとめている。以下，各章の要旨を列記する。

第２章では，本地域で記録された誘発地震の性状解明を目的として実施した一連の解析の結果について述べている。ここでは，高精度震源決定，波形間のコヒーレンスの空間分布解析，時系列解析等により，本地域で観測された誘発有感地震が２つのクラスタに分類できることを見出した。また，断層面解，マルチプレット解析，震源パラメータ解析を組み合わせ，誘発有感地震が発生した断層面の特徴を明らかにした。ここで見出された，き裂面での応力状態と誘発地震活動の関連性は誘発有感地震の特性に関する非常に重要な知見である。

第３章では誘発有感地震を発生しうると考えられる物理現象をモデル化し，それに基づく数値計算，シミュレーションを行った結果について述べている。ここでは，先行する微小地震による水圧刺激領域内での応力再分配，間隙水圧の分布，注水により生じた熱応力の影響等について検討を行っている。これにより得られた，応力降下量から見た場合，誘発有感地震は特異な現象とは見なし難いこと，および，間隙水圧の伝搬により，水圧刺激後の誘発有感地震発生を説明可能であることは，誘発有感地震現象の理解の上で重要な知見である。

第４章では，第２，３章で得られた知見を総合し，本地域での誘発有感地震発生メカニズムについて検討を行っている。ここでは，き裂型貯留層内部における誘発有感地震発生モデルを２つ提案し，観測事実，シミュレーション結果との整合性について論じている。それにより得られた，誘発有感地震はせん断応力が最大の面で発生する確率が高く，そこでの滑りを誘発するためには数MPa程度の間隙水圧上昇が必要であるという知見は，今後の誘発有感地震抑制技術開発のための重要な成果である。

第５章は結論であり，本研究の成果をまとめるとともに今後の展望について述べている。

以上，本論文は，これまで未知の部分が多かった誘発有感地震の特性を世界に例のない詳細さで解析し，それを元に誘発有感地震の発生メカニズムを検討したものである。この成果は，今後の誘発有感地震を抑制した環境適合型地下開発技術の導出へと結びつくものであり，環境科学に対する寄与は少なくない。よって，本論文は博士(学術)の学位論文として合格と認める。